AIDE AU REPERAGE TRIDIMENSIONNEL POUR LA CHIRURGIE DE LA BASE DU CRANE.

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RESUME :
Dans le cadre d'un projet de recherche interdisciplinaire, un système d'aide au repérage tridimensionnel pour la chirurgie de la base du crâne a été développé. En combinant des techniques de capteurs de position 3D, de traitement d'images et de visualisation 3D, l'orientation et la position d'un outil chirurgical sont visualisés sur un écran. L'image de la zone opérée est ainsi synthétisée à partir de coupes tomodensitométriques (TDM). Ce système a été utilisé dans plus de 300 interventions en utilisant un capteur de position 3D électro-mécanique, déplacé manuellement. Pour faciliter la manipulation, des techniques de mesures 3D sans contact ont été étudiées. Nous avons développé un capteur 3D optique, qui utilise un ensemble de sources lumineuses infra-rouges disposées sur l'instrument chirurgical. Ces diodes lumineuses sont détectées par des caméras CCD. Une précision de 1.5 mm a été obtenue. Des diodes supplémentaires situées sur des points de référence sur la tête du patient permettent de calibrer le système sans aucun procédé manuel et de suivre automatiquement chaque déplacement du crâne en effectuant la mise en correspondance avec le volume TDM. Une configuration hardware spécifique a été développée, elle permet de réaliser l'affichage de la position de l'outil sur des coupes TDM quelconques en temps réel.

Mots clés : Chirurgie assistée par ordinateur, Chirurgie de la base du crâne, Mise en correspondance et Visualisation temps réel, Capteur optique 3D, Guidage passif.

ORIENTATION AID FOR HEAD AND NECK SURGEONS

ABSTRACT :
In an interdisciplinary research project an orientation aid for skull base surgery has been developed. By combining 3D position measurement techniques, digital image processing and 3D display techniques the spatial position and orientation of an operating instrument is being visualized on a display, which shows a CT-generated view of the operation area. In more than 300 operations the system was applied by using a handguided electromechanical 3D coordinate digitizer. To yield improved flexibility and easier handling, non-contact measurement techniques were investigated. For this purpose we developed an optical measurement system, which uses a set of infrared light sources mounted on the handle of a surgical instrument. These sources are detected by array-cameras. An accuracy of 1.5 mm has been achieved. Further LEDs attached to the reference points on the head avoid the need of calibrating the measurement set-up by touching the reference points with the tip after each displacement of the skull. A special hardware was developed which permits the on-line combination of arbitrary cutting planes through the CT-volume with a pseudo 3-D representation of the head reconstructed from the CT-slices.

Key Words : Computer Assisted Surgery, Skull Base Surgery, Real-time Registration and Visualisation, Optical 3D Sensor, Passive System.

Orientation Aid for Head and Neck Surgeons

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Introduction

Computer Assisted Surgery (CAS) shall introduce "instrument navigation" into the surgeon's daily practice by providing three-dimensional position measurement techniques for the operation theatre. The surgeon's map will be a pseudo-three-dimensional presentation of the patient taken down from CT images. A measuring system capable of determining an instrument's position with respect to the patient will be the navigation guide. This system will also serve as a "flight-simulator" for realistic preoperative planning.

Two major advances can be achieved by CAS: Before starting the operation, the surgeon can "walk" through the 3D image of the proposed operation area thus gaining a realistic impression of the region and its neighbourhood. During the operation the surgeon can yield position information by simply pointing at an unidentified structure with the tip of a 3D coordinate digitizer. The respective CT sectional views are then displayed on the CRT with an indication of the position of the coordinate digitizer. By means of the application of this orientation aid, safety and quality of the operation will be increased, time consuming procedures can be avoided and novel procedures become possible in surgery.

The CAS-system has been applied in more than 300 operations by using a handguided electromechanical 3D coordinate digitizer. Recently we developed an optical measurement system to improve the flexibility of the digitizer. The visualisation of the CT-images is now supported by a special hardware which combines cutting planes through the CT volume with pseudo 3D images of the patient's head.

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State of the Art

In the course of operations at the skull base or in the region of the ears and the paranasal sinuses, intra-operative orientation can be extremely difficult due to individual variations of the patients' anatomy. The surgeon visually controls the position of the surgical instrument. Before and during the operation, several diagnostic imaging techniques are at his disposal for his orientation: X-ray films or CT image sequences, which have been prepared by preceding investigations, are displayed on lightboxes. However, because of lacking correlation between those images and his visual impression, even the experienced surgeon is sometimes not sure of the exact position of his instrument. In exceptional cases, intra-operative X-ray screening is applied. Radiation load and two-dimensionality, however, restrict application and benefit of this method. A continuous and reliable information concerning the position of the surgical instrument with respect to the anatomical structures is not possible this way. The same applies for neurosurgical operations of deep seated introcerebral lesions, for which no landmarks are available.

Stereotactic operations are done with the help of a localisation frame and an instrument holder. In the course of the operation, the position of a pathological brain process related to the fixed frame is presented on CT images which were prepared by means of preceding CT examinations. Then, an instrument holder is firmly connected to the frame. By moving the instrument along the straight path of the fixed support, without further X-ray examinations, a sample of tissue is taken at the desired position, a local lesion is set or a radiating substance is implanted. It is the neurosurgeon's task to perform the linear displacement of the instrument along the path calculated by a computer. Disadvantages of the stereotactic method are the necessity to put the patient with a frame into the CT-scanner and the restricted handling of the instruments in the fixed frame during the operation. In order to improve the stereotactic procedure, to position and to advance an instrument, devices have been developed which automatize the linear displacement of the instrument by the application of robots [1][2][3]. Other groups are working with 3D coordinate digitizers [4][5][6][7][8].

All these methods suffer from one or more of the following shortcomings:

- they only work punctually,
- the point of interest is approached along a linear path,
- there is a rigid linkage between the localisation frame fixed to the skull and the displacement of the surgical instrument,

- the displacement of the instrument is neither feeded back nor visually presented in the context of the operative field.
- the practical use is limited because of the low accuracy.

CAS-Principle

The development of the CAS system at the Aachen University of Technology predominantly aimed at supporting ENT surgery [9]. For this purpose, the CAS methods had to satisfy the following requirements:

- the object to be operated and its environment shall be continually presented on a display system,
- the position of the surgical instrument shall simultaneously be faded into the display presentation of the operative field,
- a frame attached to the skull shall be avoided and the surgeon shall be permitted to change the position of the skull during the operation.

The above requirements were fulfilled by combining 3D presentation methods with 3D coordinate measurement techniques. The surgeon uses a stylus the position of which can be measured. He tips onto points within the operative field the position of which he needs to know. Before the operation, a 3D data model of the object have to be prepared based on a complete set of computer tomograms. The measured coordinates are then correlated with the computer model to display the CT-slices of the object with faded-in position markers. Fig. 1 schematically shows the individual steps necessary for the application of the CAS-system.

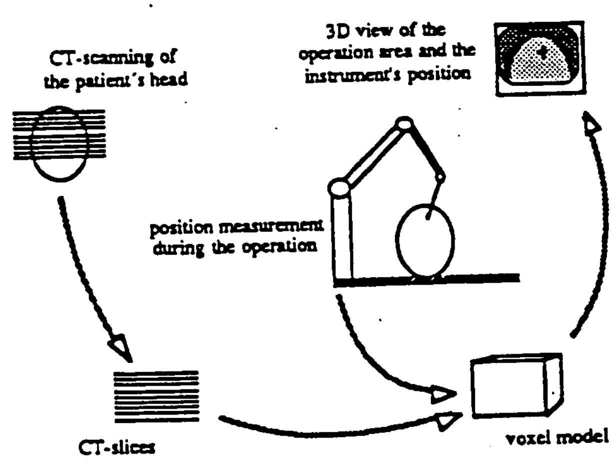


Fig. 1: CAS principle

At first radiopaque markings are attached to the patient's skull and a CT investigation is performed. After transfering the images into the CAS-system, the coordinates of these reference points are determined in the coordinate system of the CT scanner. During the operation the position of the patient is registrated by measuring the position of the reference points at his head. The derived two point-sets permit the calculation of the transformation between the coordinates of the measurement device and the patient's voxel model. After this the position of the surgical instrument can be faded into a presentation of the operative field.

3D Coordinate Measurement

The measurement system we have been using so far is an electromechanical 3D coordinate digitizer, which has been developed especially for the CAS application. The principle of construction looks similar to an industrial multi-joint robot arm (fig. 2).

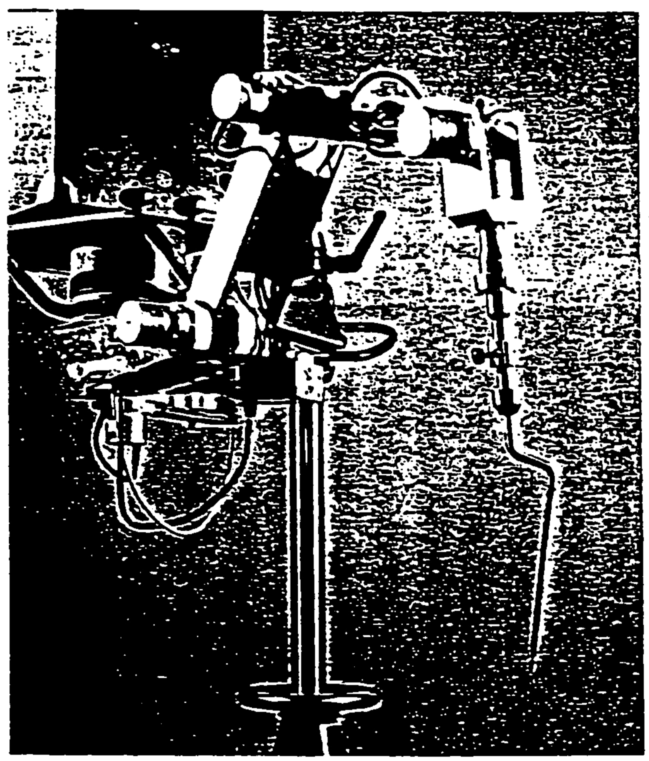


Fig. 2: electromechanical 3D coordinate digitizer

The individual arm segments of the device are connected among each other by means of rotary joints. The angles of each of the rotary joints are measured by means of rotary encoders so that the coordinates of the tip of a stylus mounted to the arm can be

calculated. Our measuring system has six joints and its first two arm elements are counterbalanced. We have applied optical increment encoders for shaft angle measurement. The accuracy of the system is better than ±0.5 mm in a measuring volume of 0.3 m^3. It has now proved its feasibility in more than 300 operations (fig. 3).

In the meantime we investigated also measurement methods which do not require any mechanical linkage to the instrument. These methods offer two major advantages:

- The surgeon can handle his instrument in the usual way.
- The position of special markers, which have been attached to the reference points on the patient's skull, can be measured continuously. Because there is no further need for the surgeon to measure the patient's position by pointing to the reference points, the risk of unnoticed patient's movement is eliminated.

An assessment of a variety of different methods for a non-contact coordinate measurement (optical, ultrasound, magnetic fields) led us to the conclusion, that the triangulation of infrared light sources by means of fixed CCD cameras seemed to be the most robust approach. Such a system was developed. Its operation will be described below.

Fig. 3: CAS operation

Optical 3D Measurement

The developed system determines the position and orientation of the patient's head and the handle of an instrument by infrared diodes, which are attached to both. The diodes are detected by cameras and the position of the instrument handle and the patient's head can be calculated by triangulation (fig. 4).

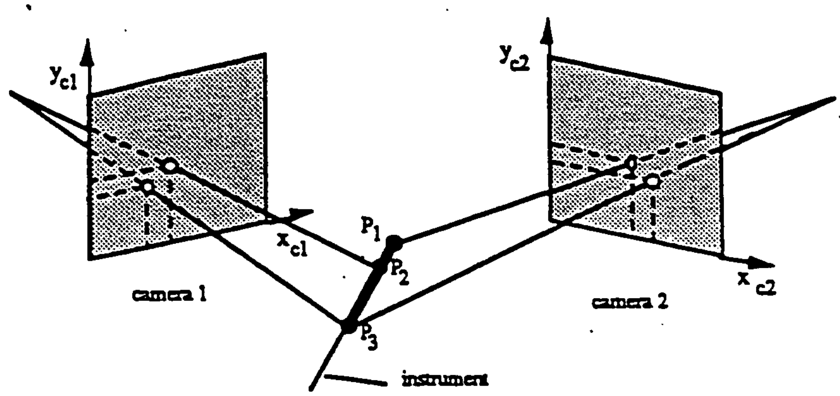
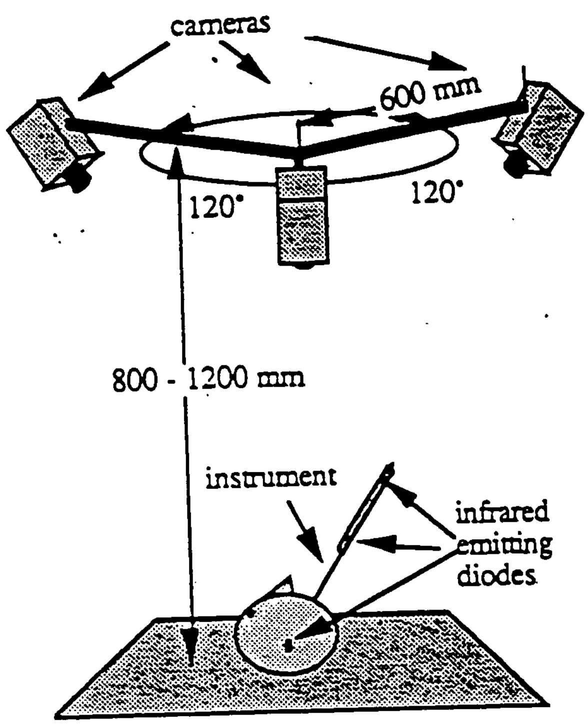


Fig. 4: principle of stereoscopic vision

As the geometrical arrangement of the diodes is known, the position of the body can be determined even if none of the attached diodes is detected simultaneusly by both of the cameras. This is a necessary precondition for the practical application of the system, since the radiation angle of the emitters is limited and some of the emitters may be screened off.

Fig. 5 shows the developed prototype system. We use three cameras to ensure that the acquisition of data remains still possible even if one camera is screened off (e.g. by the surgeon). The cameras are equipped with standard CCD array sensors. These sensors have no geometrical distortions but their low resolution (570 x 600 pixels) requires a calculation of the image coordinates with subpixel accuracy. Our investigations have shown that the resolution of the detectors can be increased to ±0.06 pixel, leading to an accuracy of less than ±0.4mm for the position of one emitter (measurement space of 600 x 600 x 400 mm^3, arrangement of cameras as shown in fig. 5).

Since the CAS application requires realtime measurement, the pixel data of the cameras (300 kByte per frame) are analyzed online by dedicated preprocessors. A reduced data set is given to a standard microprocessor which computes the position of the object. To perform these calculations, all the geometrical parameters of the cameras (e.g. focus length, distances between cameras, orientation of cameras) have to be known.



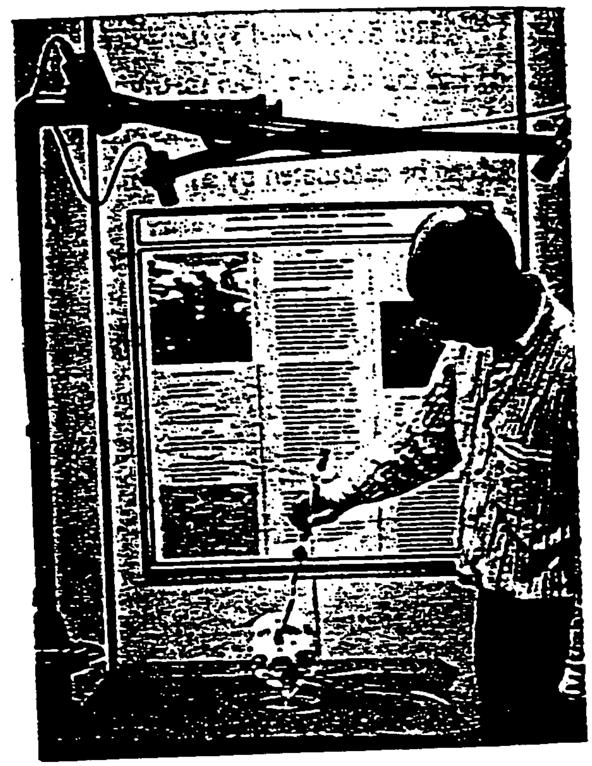


Fig. 5: prototype system

In order to determine these parameters we use a cage with 57 infrared emitters mounted on. Since the positions of these emitters are exactly known, all required parameters can be derived from their image coordinates. No calibration of the system is required if the whole camera arrangement is moved, because only the relative positions between the instrument and the patient have to be determined. This offers the possibility to move the measuring space if required (e.g. by fixing the cameras to the operation lamps).

The instrument handle is equipped with five infrared diodes as shown in fig. 6. It is seized by the distance between the two glass tubes. The shown arrangement has been chosen to obtain large radiation angles of the emitters as well as long distances between them.

A large distance between the detected emitters is mandatory for the computation of the exact position of the instrument's tip. The instrument handle is impermeable and can be sterilized by sterilizing solution, gas sterilizer or irradiation.

The system was tested successfully in the operation theatre under simulated operation conditions.

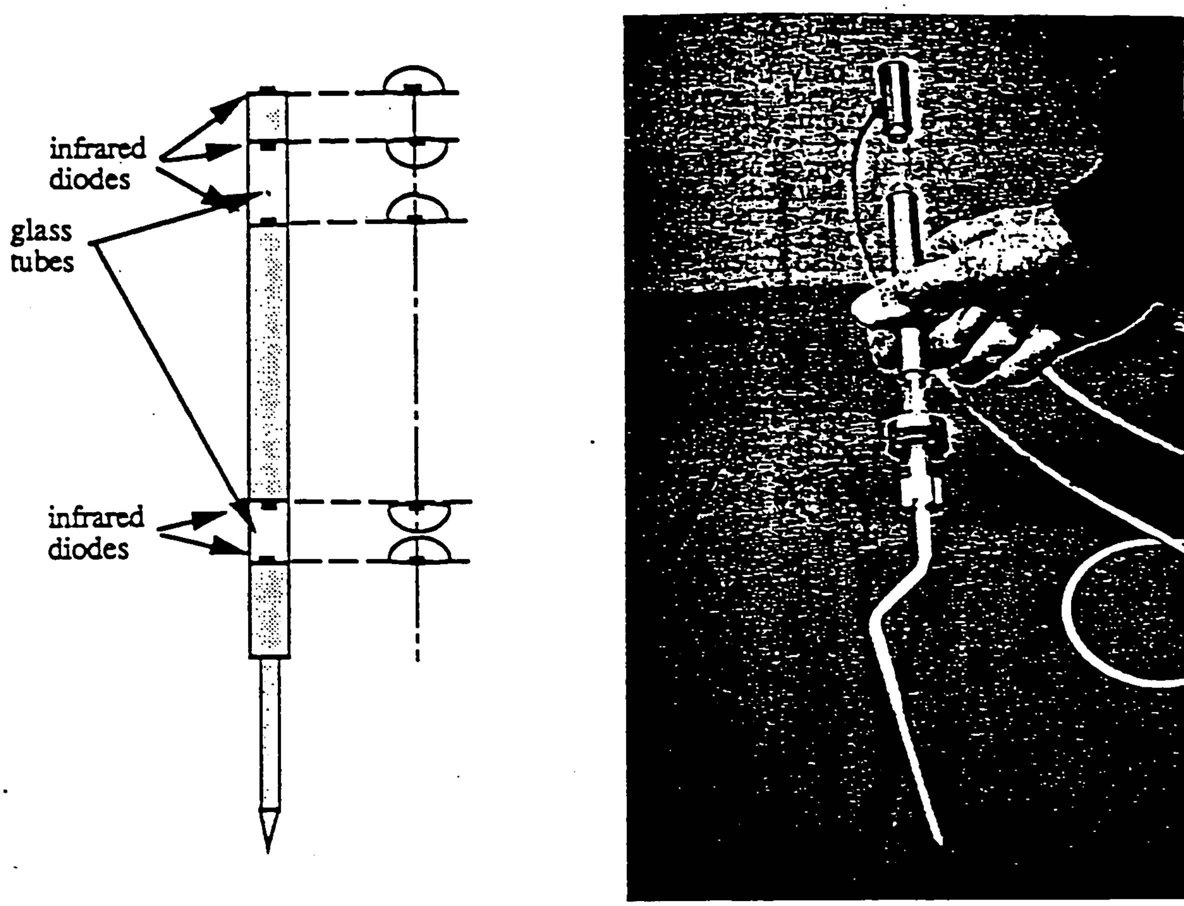


Fig. 6: instrument handle

3D Visualisation

To present three-dimensional objects, there are two basically different approaches. In case of the first approach, the boundaries of anatomical structures (organs, bones, blood vessels etc.) are determined on the given two-dimensional CT images. Then, the so gained structures are translated into a 3D model of the object's surface which can be presented as if viewed from any desired point of view. The three-dimensional impression is conveyed to the observer on account of an appropriate shading. Specific optical characteristics (colour, transparency) which amelorate the distinctness of the presentation can be related with individual objects. The disadvantage of these methods is the necessity of defining the boundaries of the objects, i.e. the segmentation of the CT images. The process of segmentation leads to a reduction of the informative content of the CT images to borderlines of organs and tissues.

In case of the second group of methods, the complete information content of the primary data is maintained. As a basis for the presentation, the entire set of 3D data is employed rather than only the surfaces of objects. Each pixel of a CT image is understood as a one volume element (voxel) of a cube of voxels which represent the object space. Visual representations of the volume interior can be presented by appropriate sectional views across the volume. Within these sectional views, the original CT sectional views may also appear.

After several experiments and thorough discussion concerning the best understanding of the display presentation, we decided to present the operative field by three perpendicular sectional views through the operative volume. This type of presenting a 3D object on a 2D medium is well known from mechanical design. Incidentally the surgeon will also get the accustomed presentation of CT images this way. In addition to the usual axial CT presentation he also gets the presentation of the corresponding perpendicular layers (sagittal or frontal display) now. These images are generated by the calculation of three perpendicular sectional views through the voxel model (fig. 2). An interpolation between given CT-sections is not necessary because the size of the voxels (1 x 1 x 2 mm) is small enough for a smooth image representation. The intersection of the three sectional views corresponds with the position of the coordinate digitizer within the operative field and is marked by a cross-hairs cursor on each sectional view.

The following equation describes the connection between the image of the display and the sectional views within the voxel model:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_0 & \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} \\ y_0 & \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} \\ z_0 & \frac{\partial z}{\partial u} & \frac{\partial z}{\partial v} \end{pmatrix} * \begin{pmatrix} 1 \\ u \\ v \end{pmatrix}$$

By means of this transformation equation, sectional views through the voxel model can be calculated under any desired angle. This is necessary if structures of objects are not distinctly presented on account of the given three perpendicular sectional views.

The three-dimensional understanding is conveyed to the oberserver on account of the fact that the sectional views can be rapidly moved forwards and backwards along any desired axis.

Recently we developed a method to show not only the position of the tip but also the shape of the instrument within the operative field (fig. 7). This became necessary because of the new application of the CAS system in the field of neurosurgery. For an ENT surgeon it is most important to know where the tip of his instrument is. A neurosurgeon is primarily interested in finding the best way to his operative field. This becomes possible with the information about the direction of the instrument. On the display the cross-hair cursor is replaced by a graphical representation of the instrument.

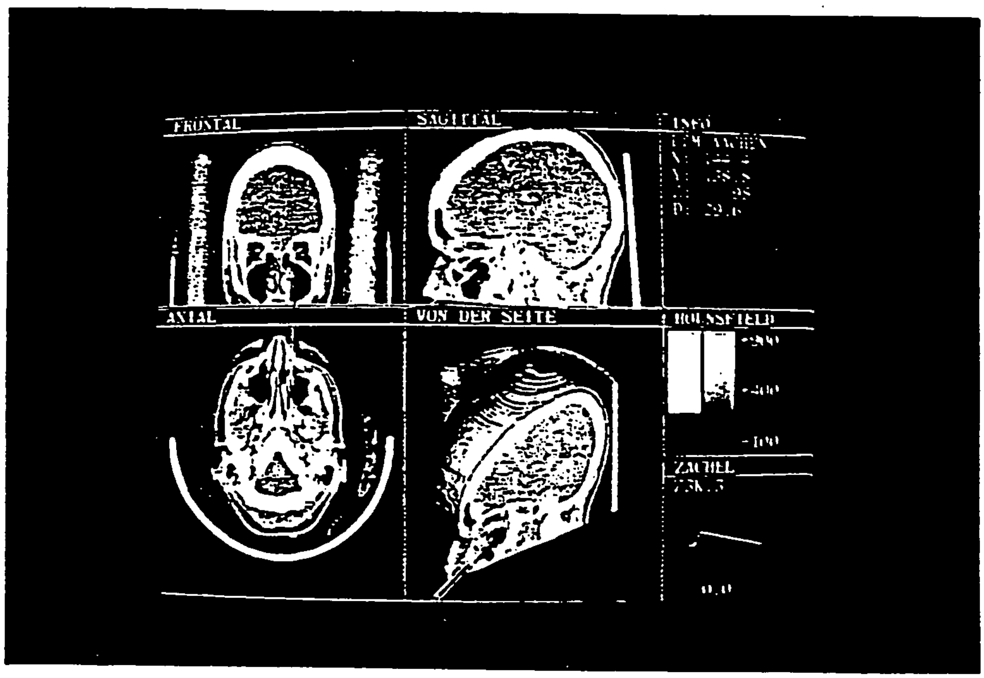


Fig.7: CAS display

In addition to the three perpendicular views of the operative field, a double oblique cutting plane through the voxel model is displayed on the screen. Three alternatives to define this cutting plane are offered.

In the first case the cutting plane is parallel to the instrument plane. Structures behind and around the instument are well visible. In the second case the cutting plane is perpendicular to the axis of the instrument. The distance between pointer tip and cutting plane is variable, so that the path to the operative field can be easily planned. The third

possibility is like a homing flight. At first a destination point. for example a brain tumor, is defined. Then the cutting plane is defined as a plane perpendicular to the instrument, which the destination point is placed on. The destination point, the point of intersection of the axis of the instrument and the cutting plane are marked with a cross-hairs cursor. The surgeon has found the right direction to the tumor when the two cursors meet each other.

When fading the projection of the stylus into a double oblique cutting plane through the volume model, as decribed above, the identification of the position and orientation of this plane appeared to be difficult. This problem has been solved by combining these cutting planes with a precalculated pseudo 3-D image of the patient's head (fig. 8).

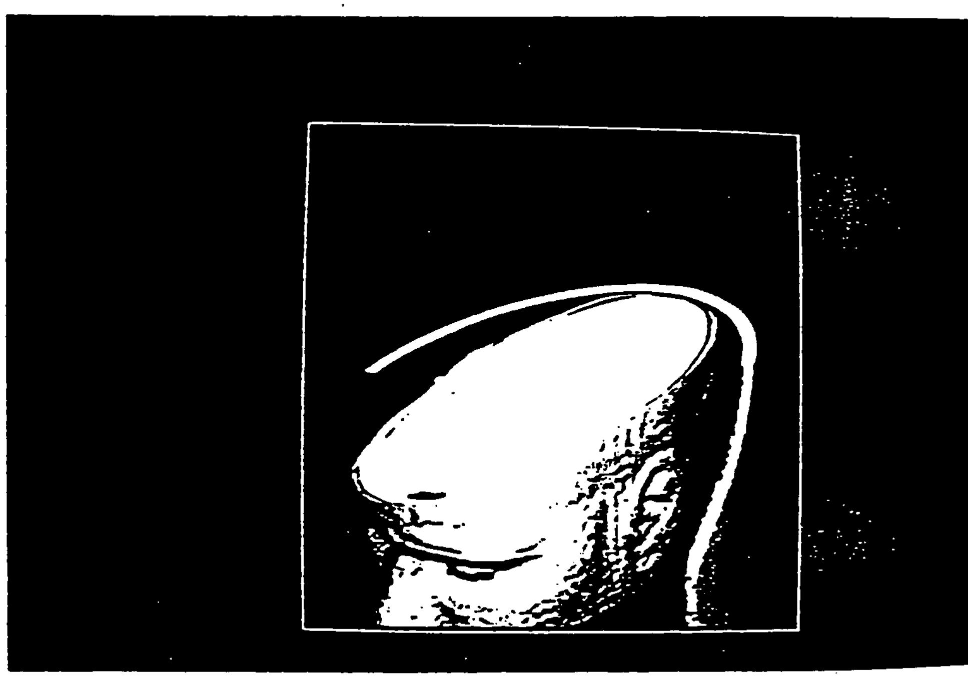


Fig.8: double oblique cutting plane with additional surface modelling

To combine a sectional view of an abitrary cutting plane with a gray-level shaded surface image without loss of speed, transformations to display the cutting plane and the surface image are calculated simultaneously. This makes it possible to decide for every pixel of the destination image, whether surface image or cutting plane is to be displayed.

This decision is made by comparing the virtual depth of the surface and the cutting plane. On the sections of the image where the surface is located behind the cutting

plane, the surface pixel has to be shown. Is, however, the cutting plane located behind the surface, the corresponding CT-voxel has to be displayed.

The virtual depth of the cutting plane is a linear funtion of the two display coordinates and can be computed on the fly. Since the depth of a natural surface can not easily be expressed by a mathematical function, a depth map describing the surface from one point of view is used.

Display Processor

To achieve a reasonable system performance a special hardware was developed which computes, independently from the CPU, all transformations necessary for displaying a combined image as mentioned.

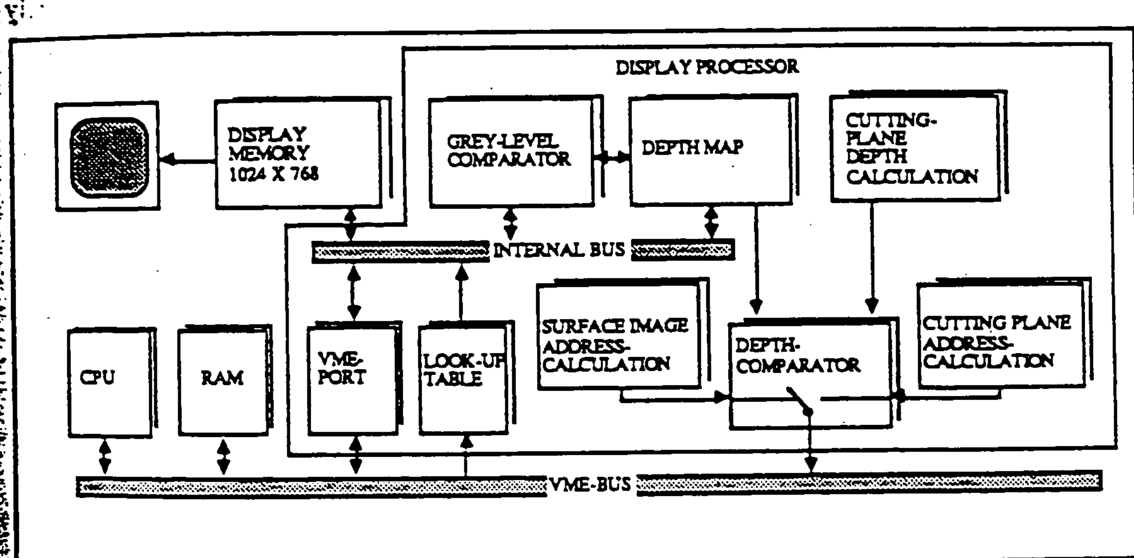


Fig. 9: computer system

An overview of the complete VME-bus based computer system is given in fig. 9. Surface images and CT-data are stored in the VME-bus RAM. For every pixel of the destination image, each one of three "image resampling sequencers" TMC 2301 by TRW calculates one coordinate of the corresponding source voxel of the cutting plane. Synchronously another two TMC 2301 calculate the source address of the corresponding surface image pixel. The virtual depth of the cutting plane for this pixel is calculated by a further TMC 2301. A hardware comparator compares the outcome with the surface depth

taken from the depth map. This depth map is stored in a local RAM area on the display processor to avoid additional VME-bus cycles during image generation. Depending on the result of the depth comparison, either the CT-voxel or the associated surface image pixel is read out of the RAM and after compression from 16 to 8 bits by an internal look-up table it is written into the display memory.

Additional graphical information like the graphical representation of the stylus or the pull-down menus used for user interaction is added by the host CPU. For the CPU, the coordinate transformer appears to be completely transparent.

Depth Map Generation

Since the "image resampling sequencers" build up the destination image column by column and row by row, a straightforward ray tracing algorithm can be easily implemented. The Coordinate Transformer is programmed to calculate subsequently cutting planes through the volume model in parallel to the viewing direction (fig. 10).

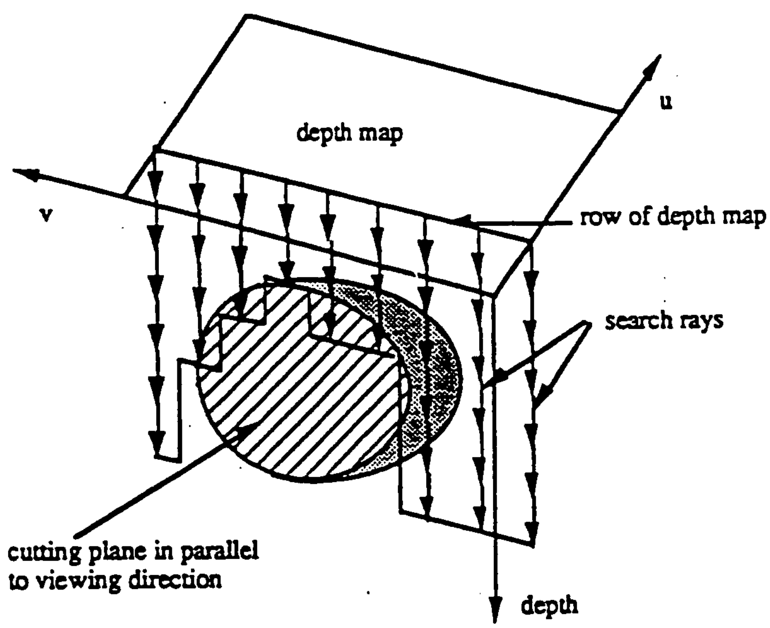


Fig. 10: depth map generation

The computation of the depth map is supported by the address generator unit. However, instead of writing the source voxel read-out of the CT-RAM directly to the display memory, they are transferred to a hardware grey level comparator. The steps within one row of one cutting plane are counted until a previously defined grey level is

exceeded. The determined count is stored at the corresponding location in the depth map. As a result each cutting plane supplies one row of the depth map. The depth map generated this way may be read out by the host CPU to compute a grey level shaded surface image.

Performance of the Display Processor

The local RAM area on the extension board is sized 512 x 512 x 9 bit, allowing four 256 x 256 bit depth charts to be used simultaneously. The generation of one depth map based on a 256xx3 voxel cube requires less than 10 seconds independent from the viewing direction. The generation of a 256 x 256 image takes about 40ms for a simple sectional view as well as for an image combined of cutting plane and surface image. The local grey-level look-up table has a size of 16 x 8 bit. Since standard CT-slices have a dynamic range of only 12 bit, the upper four bits may be used to change contrast and brightness of sectional view and surface image independently.

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